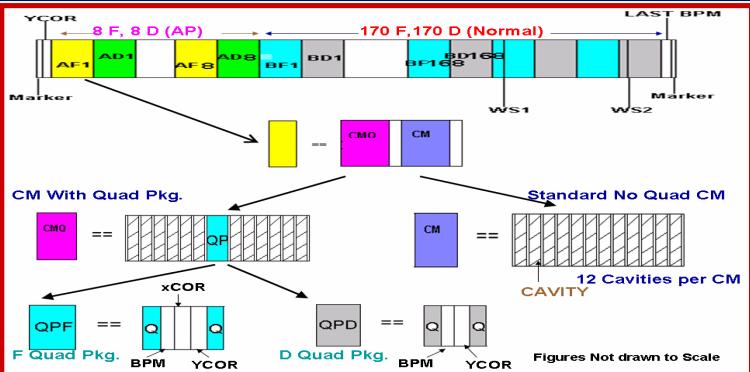


# OBJECTIVES

- Study the single-bunch EMITTANCE DILUTION in USColdLC Main Linac
- Compare the emittance dilution performance of two steering algorithms: "One-to-One" vs. "Dispersion Free Steering" under the nominal conditions
- Compare the sensitivity of the steering algorithms for conditions different from the nominal

## US COLD LC DESIGN



Cartoon of the USColdLC LATTICE DESIGN

- Cryogenic system is divided into CryoModules (CM) with 12 RF structures/ CM
- Superconducting Quads in alternate cryostats, 356 Quads (178 F, 178 D)
- Magnet Optics : FODO lattice, with  $\beta$  phase advance of  $60^\circ$  in each plane
- Initial 32 CM are provided with Autophased cavities for BNS damping
- Each quad has a BPM and a Vertical Corrector magnet; horizontally focusing quads also have a nearby Horizontal Corrector magnet

## MAIN LINAC DESIGN

- ⇒ 11.9 km length
- ⇒ 9 Cell structures at 1.3 GHz and 12 structures per cryostat
- ⇒ Total structures : 8544
- ⇒ Gradient: 28 MeV/m (TESLA TDR: 23.5 MeV/m)
- ⇒ Injection energy = 5.0 GeV
- ⇒ Initial Energy spread = 2.5 %

## BEAM CONDITIONS

- ⇒ Bunch Charge:  $2.0 \times 10^{10}$  particles/bunch
- ⇒ Bunch length = 300  $\mu\text{m}$
- ⇒ Normalized injection emittance = 20 nm-rad



TESLA Super Conducting 9-Cell Cavity

## INTRODUCTION

- USColdLC Main linac will accelerate  $e^-/e^+$  from ~5 GeV → 250 GeV: Adaptation from the TESLA TDR
- Two major design issues:
  - ⇒ ENERGY : Efficient acceleration of the beams
  - ⇒ LUMINOSITY : Emittance preservation ←

### Normalized Emittance Dilution Budget (nm-rad)

DR Exit => ML Entr. => ML Exit => IP

TESLA TDR: Hor/Vert: 8000 /20 => 10000 /30  
USColdLC: Hor/Vert : 8000 /20 => 8800 /24 => 9200 /34 => 9600 /40

- Vertical plane - more challenging:
  - ⇒ Large aspect ratio (x:y) in both spot size & emittance (400:1)
  - ⇒ ~ 2-3 orders of magnitude more difficult

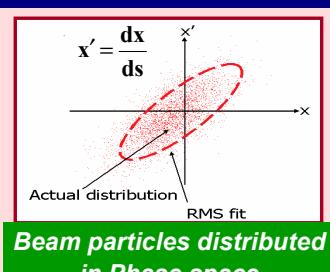
Luminosity Scaling 
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{CM}} \sqrt{\frac{\delta_{BS}}{\epsilon_y}} H_D$$

- ⇒ need high RF-beam conversion efficiency  $\eta_{RF}$
- ⇒ need high RF power  $P_{RF}$
- ⇒ SMALL NORMALISED VERTICAL emittance  $\epsilon_y$
- ⇒ strong focusing at IP (small  $\beta_y$  & hence small  $\sigma_z$ )
- ⇒ could also allow higher Beamstrahlung  $\delta_{BS}$  if willing to live with the consequences (Luminosity spread & background)

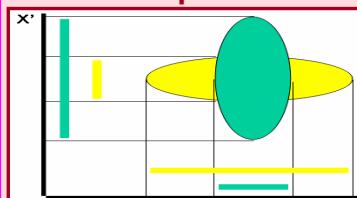
10 nm (50%)  
Vertical emit.  
Growth in  
USColdLC

## WHAT IS EMITTANCE ?

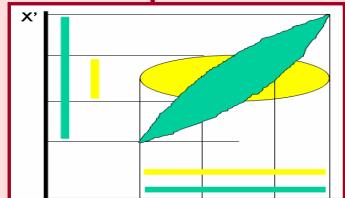
- Property of the beam
- $\sim$  Beam size \* Divergence
- Phase space area occupied by the beam
- Normalised emittance is invariant in Conservative system



### Uncoupled beam



### Coupled beam

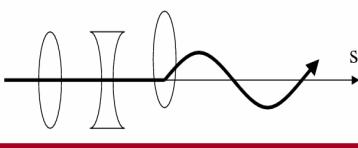


**EMITTANCE DILUTION** - In the presence of beam coupling, the product of the projections of the phase space area on the X and X' axes is a NOT a constant

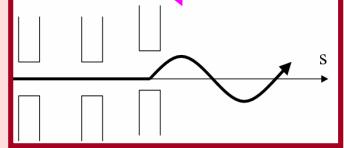
# BEAM BASED ALIGNMENT

- Alignment tolerances can not be met by *ab initio* installation – need beam-based measurements
- “Beam Based Alignments (BBA)”: techniques which provide information on beamline elements using measurements with the beam
  - ⇒ Quad strength variation
  - ⇒ “One-to-One” Correction
  - ⇒ Dispersion Free Steering
  - ⇒ Dispersion bumps, Ballistic Alignment, etc.
- **Quad Shunting:** Measure beam kick vs quad strength to determine BPM-to-Quad offset
  - ⇒ Allows estimation of beam-to-quad offset
  - ⇒ In USColdLC, it is not assumed that all quads would be shunted
    - Quads are Superconducting and shunting might take long time
    - No experimental basis for estimating the stability of the Magnetic center as a function of excitation current in SC magnets
    - In Launch region (1<sup>st</sup> 7 Quads), we assume that offsets would be measured and corrected with greater accuracy (~30 μm)
- **One-to-One (1-2-1):** Every linac quad contains a cavity Q-BPM (with fixed transverse position)
  - ⇒ Quad alignment – How to do?
    - Find a set of BPM Readings for which beam should pass through the exact center of every quad
    - Use the correctors to Steer the beam
  - One-to-One alignment generates dispersion which contributes to emittance dilution and is sensitive to the BPM-to-Quad offsets
- **DISPERSION FREE STEERING (DFS):** DFS is a technique that aims to directly measure and correct dispersion in beamline (proposed by Raubenheimer/Ruth NIMA302,1991)
  - ⇒ General principle:
    - Measure dispersion (via mismatching the beam energy to the lattice)
    - Calculate correction (via steering magnets) needed to zero dispersion
    - apply the correction
  - ⇒ Less successful so far at SLC, LEP, PEP (never reduced resulting emittance as much as predicted) – Systematics need to be understood carefully

# EMITTANCE DILUTION SOURCES

- BEAM BREAK UP
  - INCOHERENT SOURCES
    - Chromatic and Dispersive Sources
      - ↳ Misalignments:
        - ⇒ Beam-to-Quad offsets
        - ⇒ Beam-to-RF Structure offsets
        - ⇒ RF Structure pitch angles
      - ↳ Quad Roll Errors (XY coupling from rotated quads)
      - Transverse Jitter
- 

**QUAD Misalignment**



**Structure Misalignment**

## Nominal Installation Tolerances

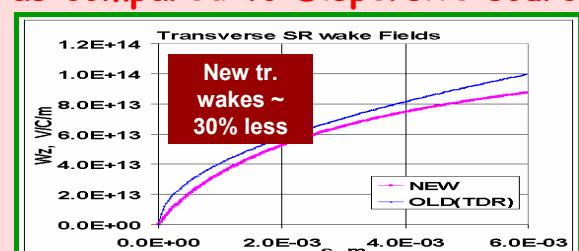
Tolerance	Vertical (y) plane
BPM Offset w.r.t. Cryostat	300 μm
Quad offset w.r.t. Cryostat	300 μm
Quad Rotation w.r.t. Cryostat	300 μrad
Structure Offset w.r.t. Cryostat	300 μm
Cryostat Offset w.r.t. Survey Line	200 μm
Structure Pitch w.r.t. Cryostat	300 μrad
Cryostat Pitch w.r.t. Survey Line	20 μrad
BPM Resolution	1.0 μm

Not mentioned in TESLA TDR

10 μm in TDR,  
expect improved  
results using NLC X-  
band Cavity BPM  
R&D

## TRANSVERSE WAKEFIELDS

- When a bunch travels through a structure with transverse offset w.r.t. the structure axis, bunch induces transverse wakefields
  - ⇒ Act back on the beam itself
  - ⇒ Short (Single bunch) & Long range
  - ⇒ SC advantage : scales as ~f<sup>3</sup>
- Single bunch Transverse wakes are very weak & cause very small emittance dilution as compared to Dispersive sources



New Transverse wake calculations (as a function of length) from Zagorodnov & Weiland 2003

# SIMULATION USING MAT-LIAR

- LIAR (LInear Accelerator Research Code)
  - ⇒ General tool to study beam dynamics
  - ⇒ Simulate regions with accelerator structures & includes wakefield, dispersive and chromatic emittance dilution
  - ⇒ Includes diagnostic and correction devices, including beam position monitors, dipole correctors, beam-based feedbacks etc
- MATLAB drives the whole package allowing fast development of correction

## ONE-TO-ONE STEERING

- Divide linac into segments of ~50 quads/segment
- Read all Q-BPMs in a single pulse
- Compute set of corrector readings and apply the correction
  - ⇒ Constraint – minimize RMS of the BPM readings
- Iterate few times before going to the next segment
- Performed for 100 Seeds

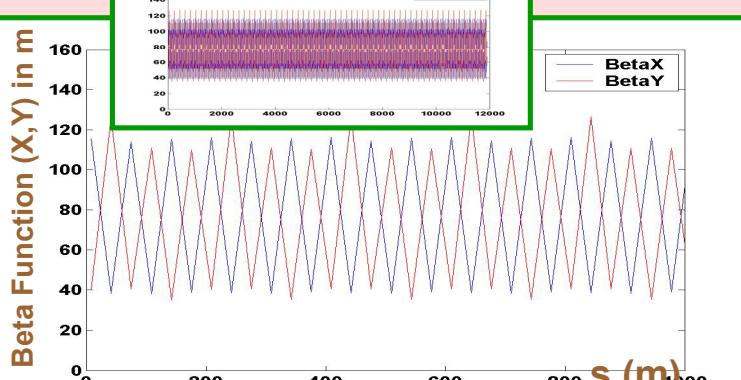
## LAUNCH REGION (1<sup>st</sup> 7 Quads) STEERING

- Emittance growth is very sensitive to this region due to low beam energy & large energy spread
- First, all RF structures are switched OFF. Beam is transported & BPM readings are extracted
- Corrector settings are computed which would result in a straight trajectory : “Gold” orbit
- The RF units are then restored and the orbit is re-steered to the Gold Orbit.

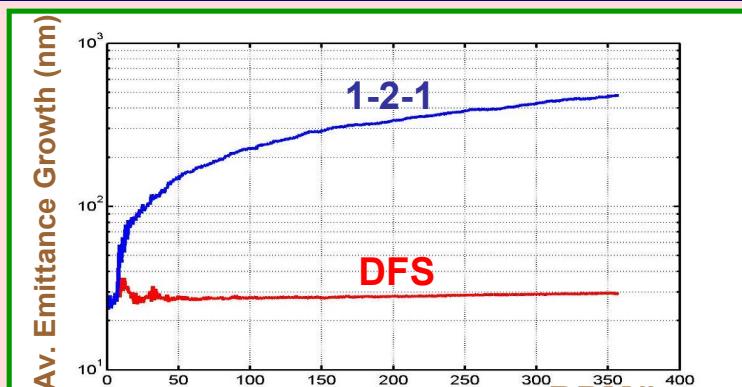
## DISPERSION FREE STEERING (DFS)

- Divide linac into segments of ~40 quads
- Two orbits are measured
- Vary energy by switching off structures in front of a segment
- Measure change in orbit & apply correction
  - ⇒ Constraint - simultaneously minimize dispersion and RMS of the BPM readings
- Iterate twice before going to the next segment
- Performed for 100 Seeds

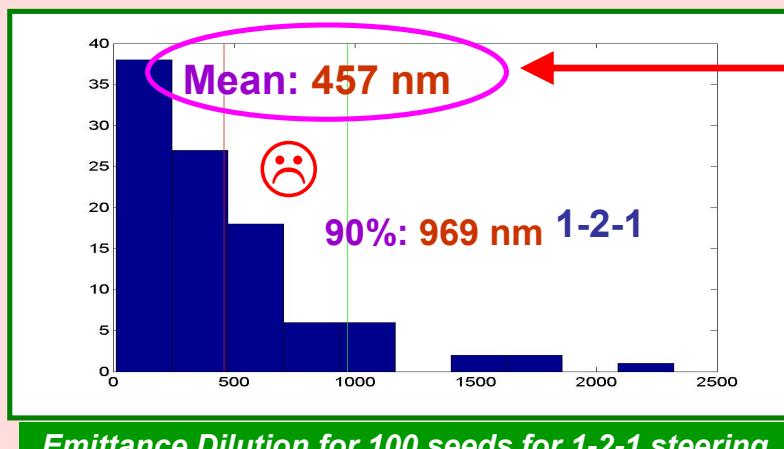
## RESULTS



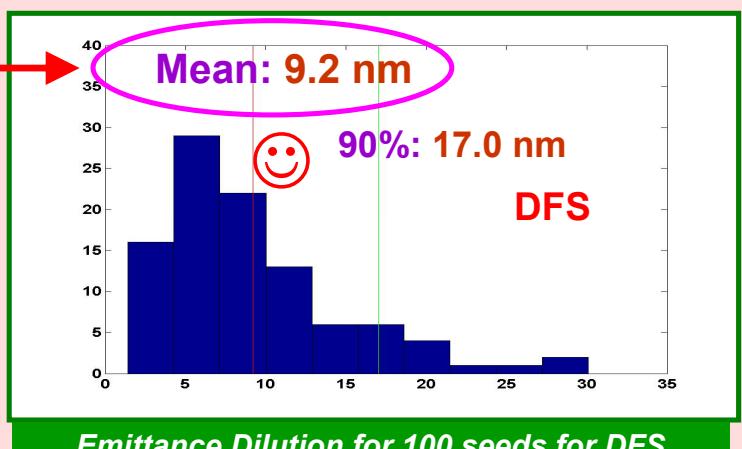
Constant Beta Lattice – Beta function corresponding to Phase advance of 60°



Average Emittance growth over the BPMs for the 1-2-1 vs. DF Steering

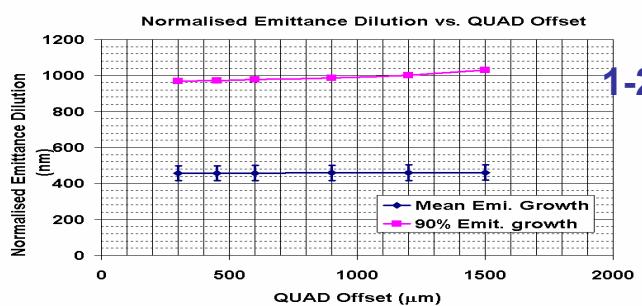


Emittance Dilution for 100 seeds for 1-2-1 steering

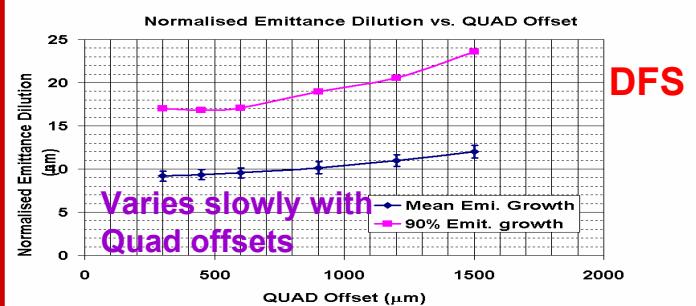


Emittance Dilution for 100 seeds for DFS

# SENSITIVITY TO VARIOUS MISALIGNMENTS

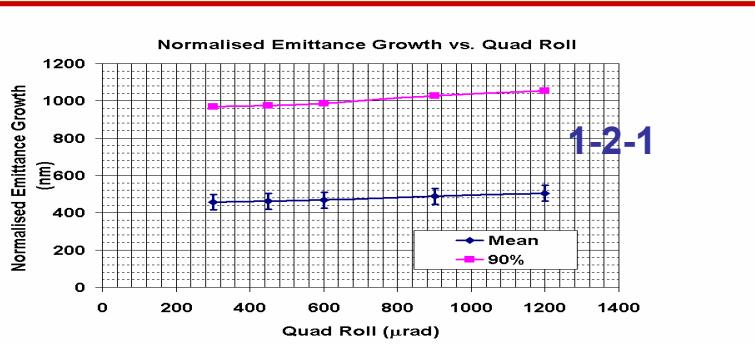


1-2-1

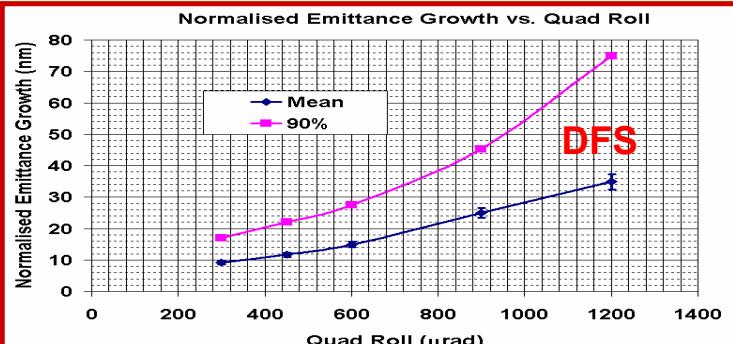


DFS

Emittance Dilution as a function of QUAD OFFSET for 100 seeds for 1-2-1 & DF Steering

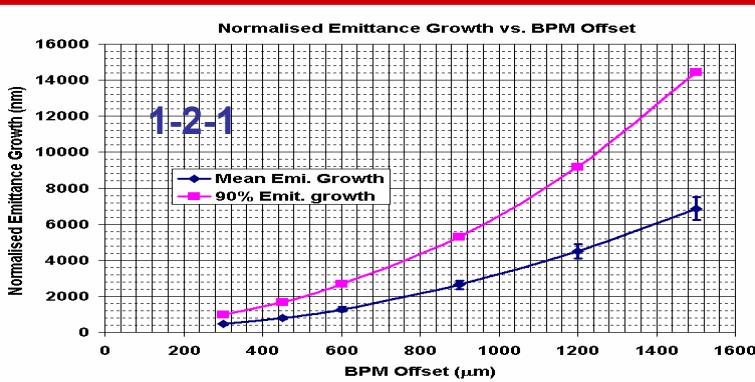


1-2-1

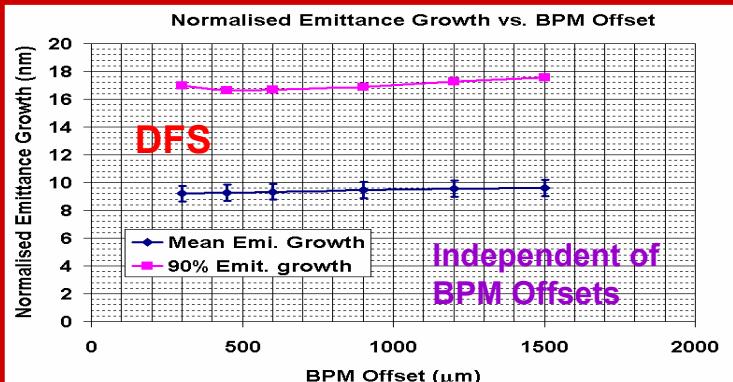


DFS

Emittance Dilution as a function of QUAD ROLL ERROR for 100 seeds for 1-2-1 & DF Steering

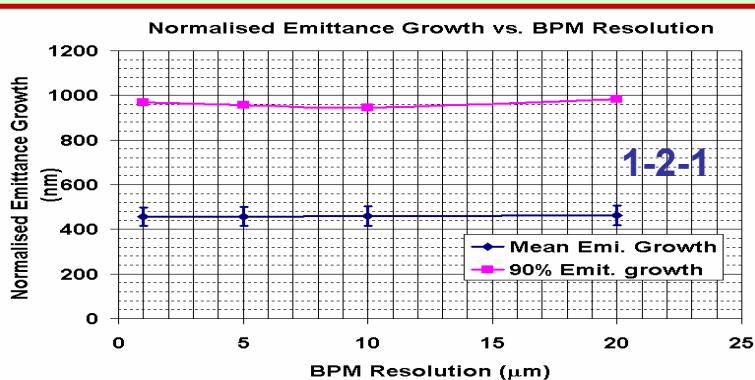


1-2-1

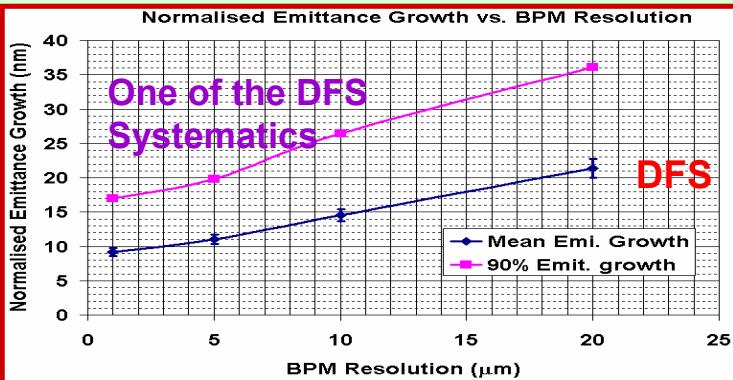


Independent of  
BPM Offsets.

Emittance Dilution as a function of BPM OFFSETS for 100 seeds for 1-2-1 & DF Steering



1-2-1



One of the DFS  
Systematics

DFS

Emittance Dilution as a function of BPM RESOLUTION for 100 seeds for 1-2-1 & DF Steering

## CONCLUSIONS

- Normalized vertical emittance growth (Single bunch) in Main Linac for 500 GeV CM USColdLC machine is simulated using MATLIAR
- DFS and 1-2-1 steering algorithm are compared in terms of:
  - ⇒ Structure-to-CM; BPM, Quad offsets; BPM resolution & Quad roll errors
- DFS algorithm provides significantly better results than 1-2-1